

1 Supplementary information

S.1 Supplementary Methods: Code for processing and filtering trajectory

All of the 3D points were processed in combination with a digitization catalog which documents the date, video ID, whether it is usable, sex of individual, start frame of digitization, impact frame, and end frame. All processing and filtering was done in Python. First, all landing data was clipped from start to end frame to remove all non-value data points before digitization begins and ends. Next, all not a number values (NaNs) were detected within each landing so the gaps could be interpolated using an unscented Kalman filter based on the FilterPy Python package.

Interpolating gaps with unscented Kalman filter

A Kalman filter uses previous positional information of a subject, derives corresponding velocity and acceleration, and uses all three to predict where the subject is most likely to be next. This means that the whole vector in 3D used by the filter is $\vec{x}(t)$ given by

$$\vec{x} = [p_x, v_x, a_x, p_y, v_y, a_y, p_z, v_z, a_z]^T \quad (\text{S.1.1})$$

For this filter a baseline of initial conditions must be supplied and the following was used

$$\vec{x}_0 = [p_x(t_0), 0, 0.1g, p_y(t_0), 500, 0.1g, p_z(t_0), 1000, -0.5g]^T \quad (\text{S.1.2})$$

All initial velocities and accelerations used are in mm/s and mm/s² correspondingly. In addition, a measurement function, H was created to allow for the known points to be effectively mapped into the measurement space the filter will use to interpolate missing values.

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (\text{S.1.3})$$

Therefore, in combination with the measurement function the measurement at any moment in time, t_i , is

$$\vec{x}(t_i) = H \cdot \vec{x}(t_i) \quad (\text{S.1.4})$$

To estimate where the missing points will be a state transition matrix is used. This matrix, F , maps the transition from $\vec{x}(t)$ to later moments in time, $\vec{x}(t + \Delta t)$.

$$F = \begin{bmatrix} 1 & \Delta t & 0.5\Delta t^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & \Delta t & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 500 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2g & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 500 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2g \end{bmatrix} \quad (\text{S.1.5})$$

For these transition states position, velocity, and acceleration are all calculated based on finite differences and the equations of motion

$$\vec{p}(t + \Delta t) = \vec{p}(t) + \vec{v}(t)\Delta t + 0.5\vec{a}(t)\Delta t^2 \quad (\text{S.1.6})$$

$$\vec{v}(t + \Delta t) = \vec{v}(t) + \vec{a}(t)\Delta t \quad (\text{S.1.7})$$

$$\vec{a}(t + \Delta t) = \vec{a}(t) \quad (\text{S.1.8})$$

Measurement noise from the known points was integrated into the interpolation through an uncertainty matrix, R .

$$R = \begin{bmatrix} \sigma_m^2 & 0 & 0 \\ 0 & \sigma_m^2 & 0 \\ 0 & 0 & \sigma_m^2 \end{bmatrix} \quad (\text{S.1.9})$$

The measurement noise used for this analysis was given by the wand calibration done in Argus, which reports a percent variance seen in the wand for a given calibration. This percentage, wand score, can be used to find the noise as a physical distance. Therefore, the measurement noise used for this interpolation was the maximum variance seen for any calibration, $\sigma_m = 21.8$ mm. In addition to the noise from the measurement a standardized Discrete Constant White Noise Model where $\sigma^2 = (0.5g)^2$ was applied along all three axes.

$$Q = \sigma^2 \begin{bmatrix} \frac{\Delta t^4}{4} & \frac{\Delta t^3}{2} & \frac{\Delta t^2}{2} \\ \frac{\Delta t^3}{2} & \Delta t^2 & \Delta t \\ \frac{\Delta t^2}{2} & \Delta t & 1 \end{bmatrix} \quad (\text{S.1.10})$$

The last feature needed for an unscented Kalman filter are the Merwe Scaled Sigma Points, which were set to the recommended parameters for this package: $\alpha = 0.001$, $\beta = 2$, $\kappa = 0$. This method was used to interpolate the gaps in the digitization of each landing. Once those values were interpolated they are smoothed with a Rauch-Tung-Striebal smoothing filter (rts_smoother). Last, those points are used to fill in the gaps in the landings original data to create trajectories with no missing time points.

Butterworth filter used on complete trajectories

With the gaps in digitization filled in the complete trajectories are filtered with a Butterworth filter. A Butterworth filters each individual trajectory by a individualized cutoff frequency, based on the noise present within that trajectory. This is done through selecting an optimum cutoff frequency at an equilibrium between large signal distortions versus low level signal noise based on the root-mean-square (RMS) error of the data when filtered at different frequencies. The RMS error is calculated by (Yu, Gabriel, Noble, & An, 1999)

$$R(f_c) = \sqrt{1/N \sum_i^N (p_i - \hat{p}_i)^2} \quad (\text{S.1.11})$$

The RMS error can then be plotted across the range of filter frequencies and a cutoff can be found between where the data has high RMS values, large signal distortions included in the data, and low level RMS error values, suggestive of low level noise and higher resolutions filters having diminishing returns. For this data a second order Butterworth was done where the frequency range of cutoffs was 0.1 – 10 Hz with 0.1 Hz increments and a 95% cutoff. This means the following was done for each trajectory. The RMS error values are calculated for a trajectory when filtered across the range of frequencies given. Linear regressions are then repeatedly done for the points sequentially, adding to the data included, starting from 10 Hz (strongest filter) to 0.1 Hz (weakest filter). Once the $r^2 < 0.95$ for the linear regression, the previous frequency is identified as the cutoff frequency which will be the actual filter used on the trajectory. In essence, this technique finds the elbow typically present in the RMS error plots allowing selection of a filter which only removes the largest deviations, most likely to be significant signal distortions, in a given dataset.

S.2 Velocity and τ Trajectories

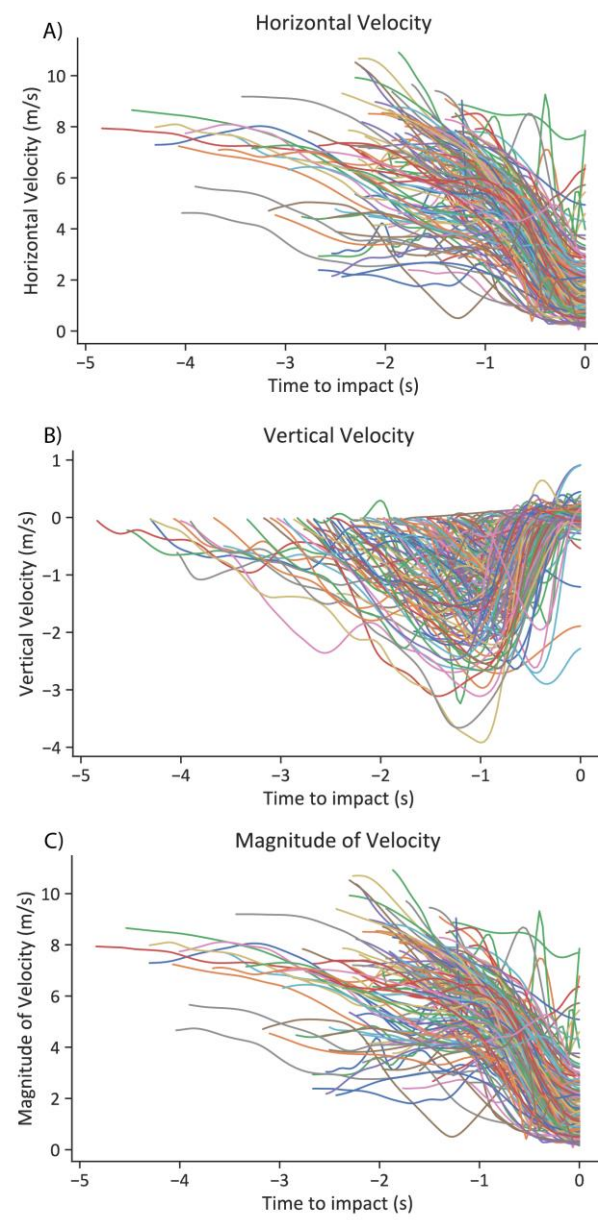


Fig. S1. Horizontal, vertical and magnitude of velocity plots

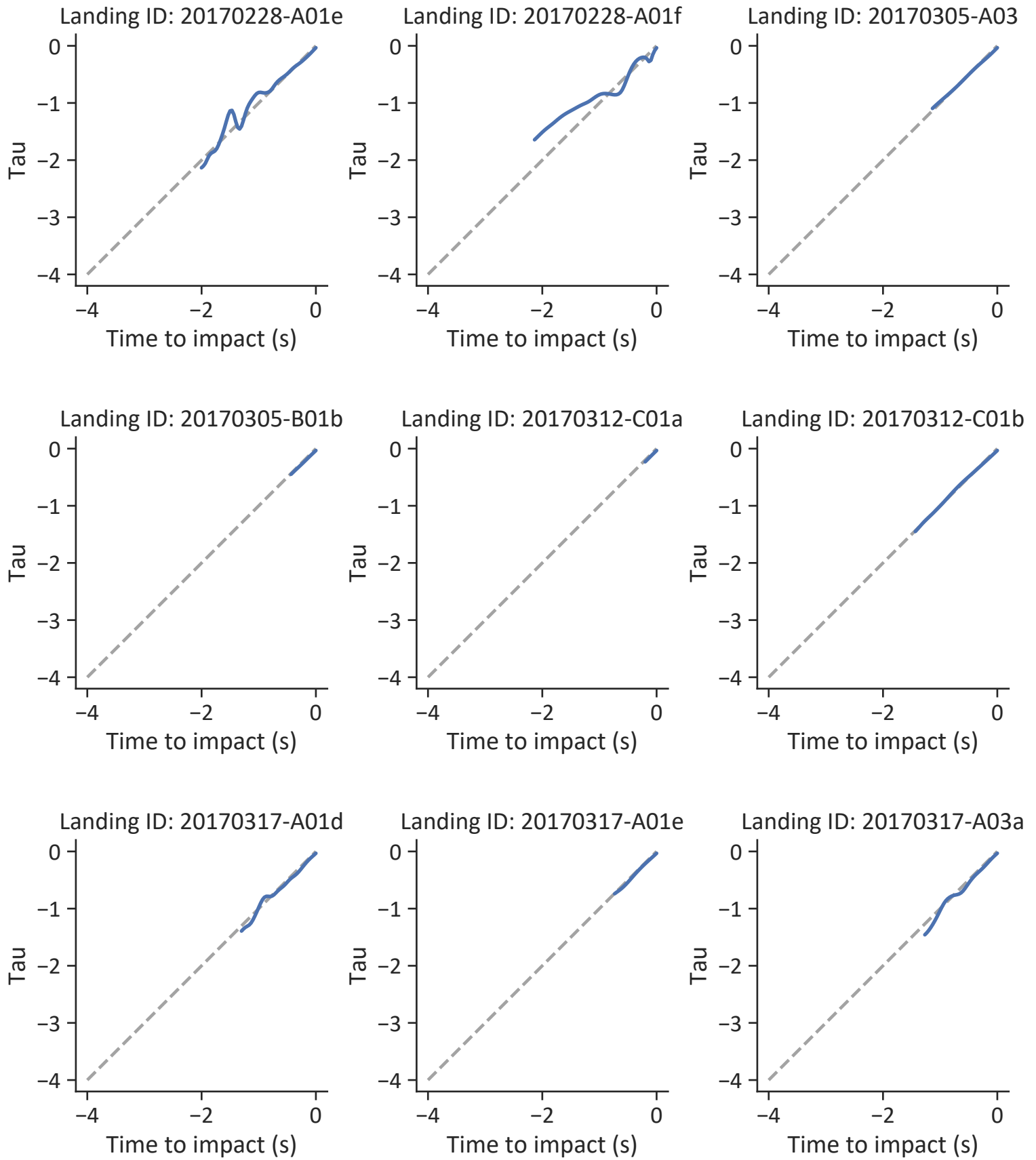


Fig. S2. Sample of Individual plots of τ for each landing

References

- Jackson, B. E., Evangelista, D. J., Ray, D. D., & Hedrick, T. L. (2016). 3D for the people: multi-camera motion capture in the field with consumer-grade cameras and open source software. *Biology Open*, 5(9), 1334–1342. doi: 10.1242/bio.018713
- Lee, D. N., Davies, M. N. O., Green, P. R., & Van Der Weel, F. R. (1993). Visual control of velocity of approach by pigeons when landing. *Journal of Experimental Biology*, 180, 82–104.
- Yu, B., Gabriel, D., Noble, L., & An, K. N. (1999). Estimate of the optimum cutoff frequency for the Butterworth low-pass digital filter. *Journal of Applied Biomechanics*, Vol. 15, pp. 318–329. doi: 10.1123/jab.15.3.318